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(HBCU/MI) ULTRALOW NOISE MONOLITHIC QUANTUM DOT PHOTONIC OSCILLATORS

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Final Report

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14. ABSTRACT
Three different nanostructured semiconductor lasers were studied - the quantum dot passively mode-locked laser, the dual-mode quantum dot laser, and the optically-injected quantum dot distributed feedback laser. The key milestones achieved were: 1.) the use of external optical feedback to reduce the timing jitter of the pulsed lasers from 295 fs/cycle to 32fs/cycle, 2.) experimental determination of the optimum temperature range and absorber-to-gain length ratio, 3.) Delay Differential Equation modeling to study the nonlinear dynamics specific to the quantum dot medium, including the derivation of new equations for this purpose, 4.) the demonstration of dual-mode lasing in a quantum dot distributed feedback device using optical injection to generate microwave, mm-wave and THz signals, and 5.) the generation of relaxation oscillations over a continuous 5 octaves (below 1 GHz to 40 GHz) in an optically-injected quantum dot laser.

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Abstract: three different nanostructured semiconductor lasers were studied – the quantum dot passively mode-locked laser, the dual-mode quantum dot laser and the optically-injected quantum dot distributed feedback laser. The key milestones achieved were: 1) the use of optical feedback to reduce the timing jitter of the pulsed lasers from 295 fs/cycle to 32 fs/cycle, 2) experimental determination of the optimum temperature range and absorber-to-gain length ratio, 3) Delay Differential Equation modeling to study the nonlinear dynamics specific to the quantum dot medium, (including the derivation of new equations for this purpose), 4) the demonstration of dual-mode lasing in a quantum dot distributed feedback device using optical injection to generate microwave, mm-wave and THz signals and 5) the generation of relaxation oscillations over a continuous 5 octaves (below 1 GHz to 40 GHz) in an optically-injected quantum dot laser.

Objectives

The following bulleted list contains the Statement of Work for the 3 – year grant:

Months 1 – 12

- Experimentally perform an in – depth analysis of several passively mode locked quantum dot laser devices, and study performance characteristics of various types of devices (packaged v/s unpackaged, and TE cooled v/s not cooled), in order to identify the best devices for experiments involving free – running and/or external optical feedback configurations, and to evaluate the suitability of these devices for each case.
- Experimentally study the mode – locking behavior of the devices selected above under optical feedback, with the introduction of a controlled external feedback loop.
- Experimentally study the effect of introducing an external feedback loop on the behavior of a quantum dot distributed feedback (QD DFB) laser.
- Use the Vladimirov – Turaev Delay Differential Equation (DDE) model to numerically simulate mode locking behavior in actual quantum dot devices over a range of temperatures.

Months 13 - 24

- Extend the optical feedback experiments to include the effect of temperature variation, in order to study the effect of feedback on device performance over a wide range of temperatures.
- Use fundamental physical models to simulate the variation of parameters in the DDE model that are otherwise difficult to obtain (for instance, the variation of parameters such as the linewidth enhancement factor and the carrier relaxation ratio over temperature).

Months 25 – 36

- Extend the DDE model to explicitly include the effect of optical feedback, so as to enhance its capabilities as a comprehensive and powerful theoretical framework to guide the design and analysis of mode locked quantum dot lasers as part of low noise, low jitter optical and photonic systems.

All of these original objectives of the grant were met except the last one, which proved unfeasible within the timeframe of the research. Additional funding was received from AFRL/RYDP through AFOSR to sponsor the tasks below in Months 1-12. This work carried over into months 13-24 and various journal publications in including a series of 3 journal articles on dual-mode quantum dot lasers for microwave to THz frequency generation. *Applied Physics Letters*, *Optics Express*, and *IEEE Photonics Journal* and *IEEE Journal of Selected Topics in Quantum Electronics* resulted.

- Design, fabricate and test dual-mode quantum dot lasers.
- Study and develop the design strategies required to improve the mode stability and linewidth of the quantum dot dual-mode laser.

- Evaluate the tuning capability of the two-color emission in multi-section QD DFB lasers.

The scholarly output of the 3-year grant can be categorized by the 3 different semiconductor lasers that were studied: 1) the quantum dot passively mode-locked laser 2) the dual-mode quantum dot laser, and 3) the optically-injected quantum dot distributed feedback laser.

Accomplishments

Part 1 The Quantum Dot Mode-Locked Laser

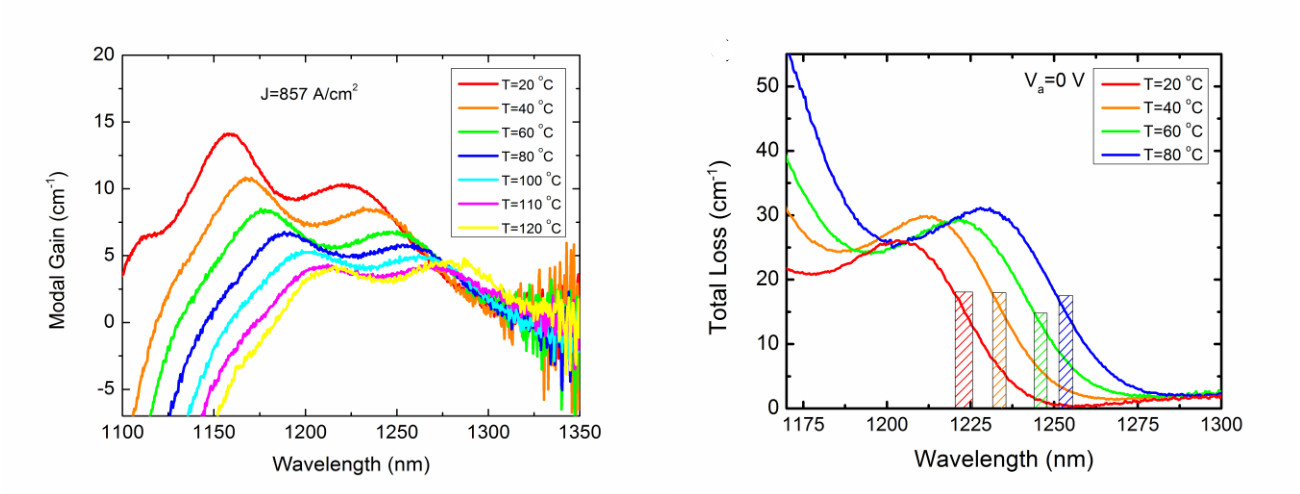
The QD mode-locked laser was characterized through an all-microwave measurement technique. The experimental phase noise spectra at different harmonics were in good agreement with previous diffusion-based theory that was developed at CalTech. This theory was validated for a QD mode-locked laser device for the first time. In fact, our measurement technique provided a simple way to characterize the noise performance of any passively mode-locked laser. Furthermore, the average pulse-to-pulse rms timing jitter reduced by an order of magnitude from 295 to 32 fs/cycle via external optical feedback. This work was described in detail in the paper by C.-Y. Lin et al. "Microwave Characterization and Stabilization of Timing Jitter in Quantum-Dot Passively Mode-Locked Laser via External Optical Feedback," *IEEE J. Special Topics Quantum Electron*., **17**(5), 1311-1317 (2011). This work lead to the discovery that the optimal temperature for operating the quantum dot mode-locked lasers for low RF linewidth and jitter is from 60-70C. The explanation for the cause of this behavior was successfully explained in Year 3 by PhD student Jesse Mee, who obtained his degree in Summer 2013. He continues to work in the Space Vehicles Directorate of AFRL/Kirtland. Dr. Mee's work focused on understanding and improving the pulse characteristics of two-section QD passively MLLs over broad temperature excursions ([12], [16], [17], [19]), wherein, he studied the impact of the absorber length to gain length ratio. As a prerequisite to optimizing pulse characteristics, knowledge of how to construct the cavity layout for two-section MLLs is needed. As mentioned previously, our previous work has followed a methodology based on a microwave photonics approach ([1], [2], [4]), wherein two characteristic functions describing the boundary for the onset of mode-locking are used to predict regions of mode-locking stability for a given cavity geometry. In this approach, the regions predicting mode-locked operation are represented on a plot of cavity geometry (absorber-to- gain length ratio) vs pump current density, wherein, the lower bound is described by the expression:

$$\frac{L_a}{L_g} > \exp\left[2\cdot\left(\frac{J_{tr}-J}{b}\right)\right]\left(\frac{g_{\max}}{a_0}\left[1-\exp\left(\frac{J_{tr}-J}{b}\right)\right]+\frac{a_i}{a_0}\right) \quad (1)$$

Similarly, the upper bound is given by the expression:

$$\frac{L_a}{L_g} = \frac{g_o-\alpha_m-\alpha_i}{a_o+\alpha_m+\alpha_i} \quad (2)$$

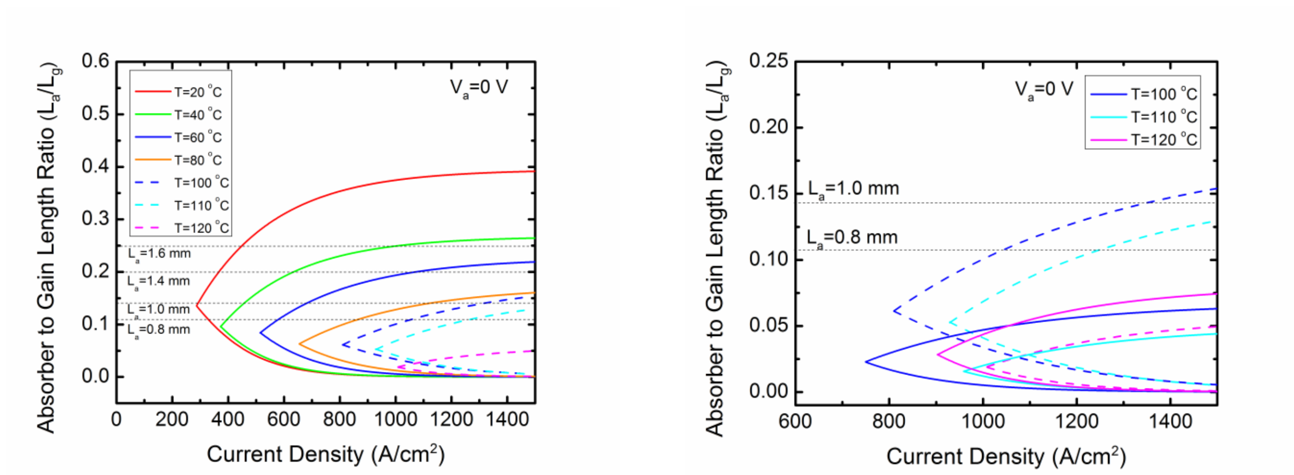
The strength of this approach lies in the fact that all the parameters appearing in the analytic expressions can be measured; namely, the static gain and loss characteristics. The segmented contact method is utilized to measure the modal gain and total loss spectra over a wide temperature range up to 120 ^{o}C and over a wide range of gain-section current and saturable absorber section reverse voltages. Using the experimental gain and absorption spectra (Fig. 1a and b) to derive appropriate inputs, the model described above in equations (1) and (2) was used to predict regions of mode-locking stability for a given cavity geometry as depicted in Fig. 2.



1a.)

1b.)

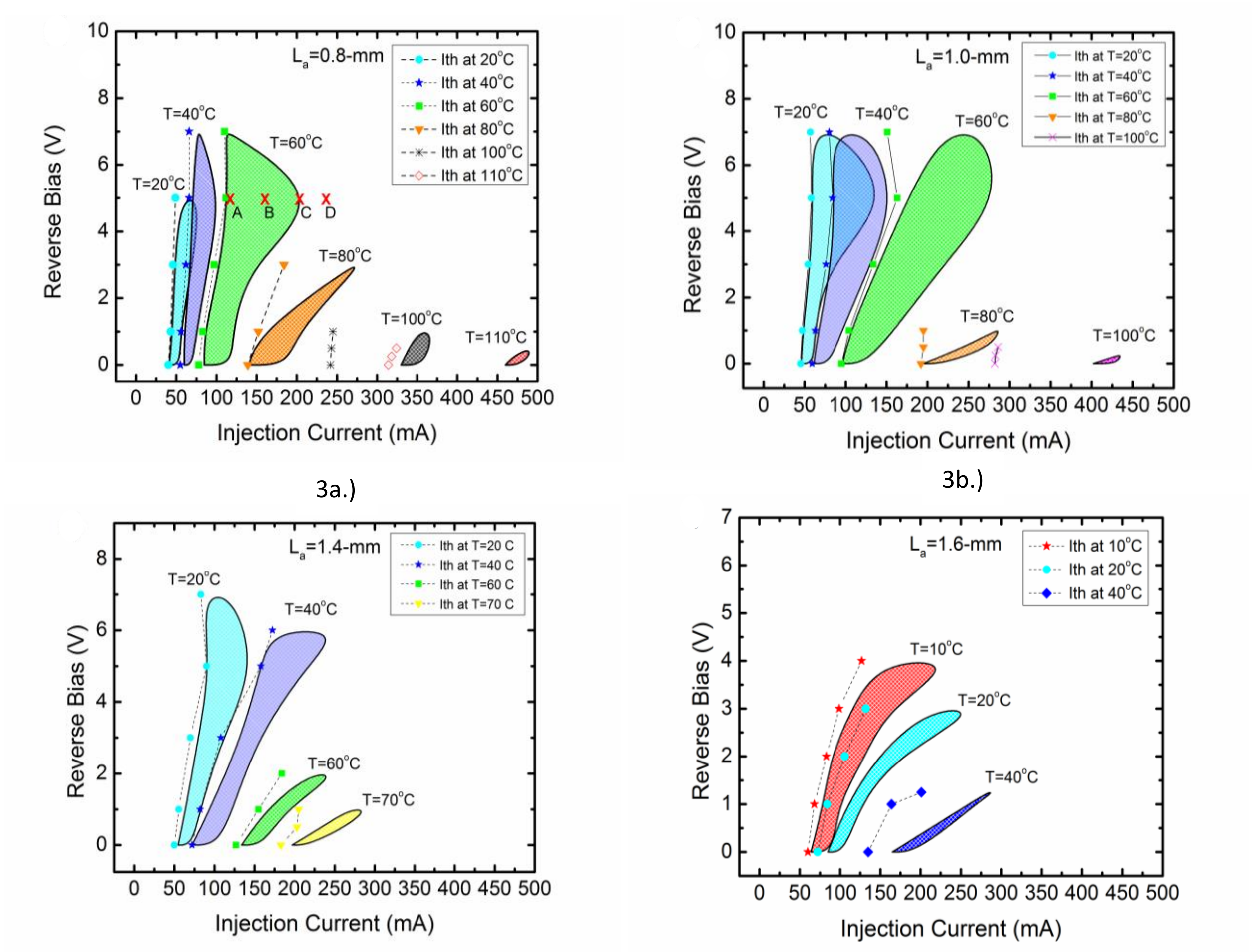
Fig. 1a. Measured modal gain spectra for a constant current density of 857 A/cm^2 at 20, 40, 60, 80, 100, 110 and 120 ^{o}C. b.) Measured total loss spectra for absorber reverse bias of 0 V from T=20 to 80 ^{o}C.



(2a)

Fig. 2a.) Mode locking stability map for 0 V applied reverse bias as predicted by the analytical model in equations (1) and (2) using the measured GS gain and absorption data (solid plots) and measured ES gain and absorption data (dashed plots). The horizontal dashed lines represent the absorber to gain length ratios of the devices used in this study b.) Expanded view of dashed plots in Fig. 2a.) – comparison of model predictions from the ground state (solid plots) and the excited state (dashed plots) for 100 to 120 ^{o}C with grounded saturable absorber.

The path to a QD MLL capable of broader temperature operation suitable for integration with Si-photonics was discussed and demonstrated in previous works by our group. To this end, a complete set of QD MLLs having different absorber lengths for the same fixed cavity length was analyzed in this grant [12]. The active region for the devices used in these experiments consists of 6-stacks of InAs quantum dots embedded in InGaAs quantum wells, separated by GaAs barriers, known as the Dots-in-a-Well (DWELL) laser structure. Multi-section laser processing was used to fabricate the 5-µm ridge waveguide devices. Each device contains an intra-cavity saturable absorber that is electrically isolated from the gain section via proton implantation. The total cavity length is a constant 8.0-mm in all cases; however, the length of the intra-cavity absorber (L_a) is varied among the different devices. During the grant, 4 different devices having L_a = 0.8-mm, 1.0-mm, 1.4-mm, and 1.6-mm were examined. The resulting absorber to gain-section length ratios are 0.11, 0.14, 0.21, and 0.25 respectively. In these two-section lasers, the facets are HR(95%)/AR(5%) coated with the absorber adjacent to the HR-coated facet. Gain and absorption data was measured on a multi-section optical emitter that had 16 electrically-isolated 500-µm sections and a 3.5-µm ridge waveguide.



3a.)

3b.)

3c.)

3d.)

Fig. 3. Contour maps depicting the regions of fundamental mode-locking (5 GHz) where the measured FWHM of the optical pulse was less than 19 ps for a.) L_a=0.8-mm, b.) L_a=1.0-mm, c.) L_a=1.4-mm, and d.) L_a=1.6-mm. These absorber lengths are depicted in the modeled mode-locking stability maps in Figs. 2a.) and 2b.). The plotted symbols show the threshold current at each temperature and reverse voltage.

As seen from a careful comparison between Figs. 2 and 3, our modeling approach, which includes the inputs derived from the gain and loss spectra at the ground state and excited state wavelengths of the quantum dots (Fig. 1), creates theoretical stability maps that closely follow the experimental results. Furthermore, Dr. Mee's work found that the unsaturated absorption is a critical parameter that strongly influences the range of currents above threshold that produce stable mode-locked pulses. The numerous devices tested by him under various operating conditions exhibited minimum values of unsaturated absorption around 60°C, as seen in Fig. 4 [12]. This minimum in absorption corresponded to the same temperature at which the time-bandwidth product of the quantum dot mode-locked laser minimized, an important finding to the quantum dot laser community that was reported in [12].

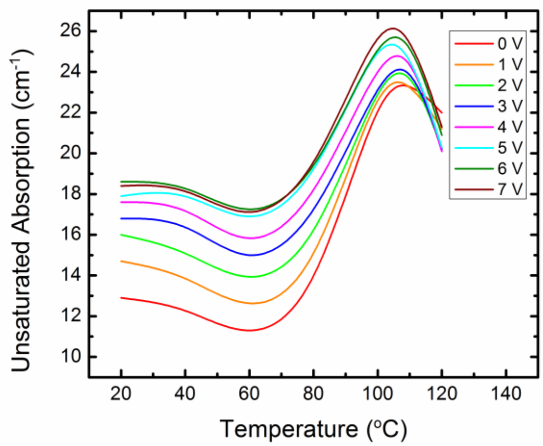


Fig. 4. Experimentally measured unsaturated absorption at the gain peak over the temperature range from 20 to 120 ^{o}C for saturable absorber reverse bias of 0 to -7 V. The absoption is found to reach a minimum around T=60 ^{o}C. This is a consequnce of the gain peak/abosrption peak walk off.

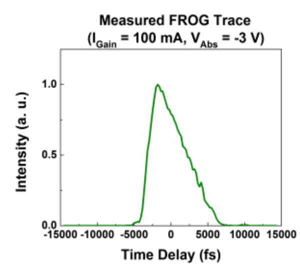
Detailed results of all devices studied can be found in the recent paper by J. K. Mee et al, "Temperature Performance of Monolithic Passively Mode-Locked Quantum Dot Lasers: Experiments and Analytical Modeling," *IEEE J. Sel. Top. Quantum Electronics*, **19**(4) 1101110 (2013).

On the theory/simulations side, we investigated the dynamics of a nonlinear delay differential equation (DDE) model for passive mode-locking in semiconductor lasers, when the delay model is seeded with parameters extracted from gain and loss spectra measured on an actual quantum dot laser structure. The approach used relies on narrowing the parameter space of the model by constraining the values of most parameters to values extracted from gain and loss measurements at threshold. The impact of the free parameters, namely, the linewidth enhancement factors that are not available from the gain and loss measurements, on the device output is then analyzed using the results of direct integration of the delay model. In addition to predicting experimentally observed trends such as pulse trimming with applied absorber bias, the simulation results offer insight into the range of values of the linewidth enhancement factors in the gain and absorber sections permissible for stable mode-locking near threshold. Further, the simulations show that this range of permissible values is significantly reduced under the application of a bias voltage on the absorber section, thereby suggesting that an applied bias is not only required for pulse trimming, but also a reduction in the linewidth enhancement factor, which is important for telecomm and datacomm applications where such devices are sought as pulsed sources, as well as in military RF photonic applications, where mode-locked diode lasers are used as low noise clocks for sampling. This work was described in an SPIE Photonics West 2012 conference paper by R. Raghunathan et al. “Delay Differential Equation-Based Modeling of Passively Mode-Locked Quantum Dot Lasers using Measured Gain and Loss Spectra.”

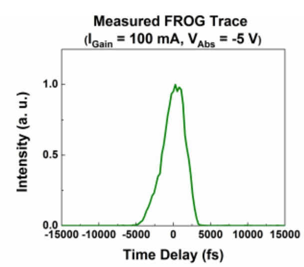
Further, it was found that the carrier relaxation ratio of a device, which is defined as the ratio of the absorber relaxation time to the gain relaxation time, can be extracted from gain and loss data measured on the device, as an important alternative to pump-probe techniques. A novel expression for this parameter was derived by PhD student Ravi Raghunathan [8], who graduated in Summer 2013:

$$\Gamma = \left(\frac{Q}{2Gs}\right) = \frac{(a_0 + \alpha_i)L_a}{2(g_{\mathrm{mod}}(J) - \alpha_i)L_g s} \tag{3}$$

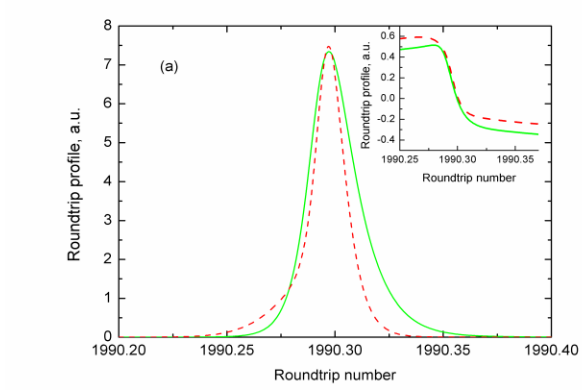
A more generic version of this expression was further studied by R. Raghunathan, and used as part of the DDE modeling-framework as a powerful technique to understand, control and potentially exploit the nonlinear dynamics exhibited by an individual device, thereby providing invaluable insight into understanding abrupt transitions in the dynamics of the device output, such as the sudden switching of pulse asymmetry. This phenomenon was confirmed for the first time with direct FROG measurements of the laser, as seen in Fig. 5 below:



a.)



b.)



c.)

Fig. 5. Pulse-asymmetry switching: a.) and b.) measured FROG traces, b.) model simulations.

Complete details of this work can be found in a recent publication [10] by R. Raghunathan et al entitled, "Pulse Characterization of Passively Mode-Locked Quantum-Dot Lasers Using a Delay Differential Equation Model Seeded with Measured Parameters," *IEEE J. Sel. Top. Quantum Electronics* **19**(4), 1100311 (2013). A further publication [18] entitled, "Modeling and characterization of pulse shape and pulse train dynamics in two-section passively mode-locked quantum dot lasers," *SPIE Proceedings* of Photonics West 2013 discusses the use of the DDE model to predict regimes of stable harmonic mode-locking in a two-section passive QDMLL.

Part II: The Dual-Mode Quantum Dot Laser

A new direction of research inter-twining our previous efforts in optical injection and external optical feedback emerged as a promising pathway toward THz generation, when a dual-mode laser operating in the excited and ground states of an InAs quantum dot was realized by combining asymmetric current pumping of the laser cavity and external optical feedback stabilization. As a first step of this research, PhD student Nader Naderi fabricated a quantum dot distributed feedback laser device as shown below in Fig. 6:

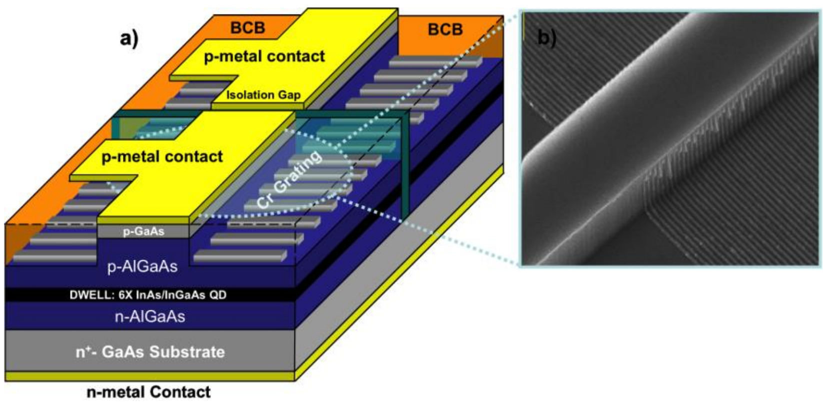


Fig. 6. (a) Oblique schematic view of the epitaxial layers and two-section cavity structure of the InAs QD LLC-DFB laser. (b) Oblique SEM image of the 100 nm wide chromium grating lines adjacent to the ridge waveguide processed by electron-beam lithography and metal evaporation.

This device was then demonstrated by Naderi as a source for two-color or dual-mode emission, when two peaks separated by 8 THz were seen at the output of the following experimental setup depicted in Fig. 7. The point here is that the device should be compact and tunable, so further experiments were required to assess these goals.

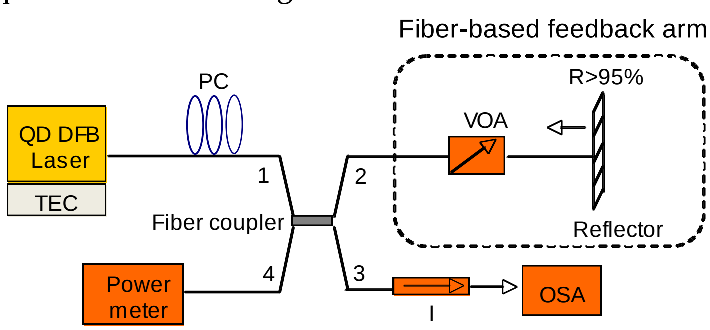


Fig. 7: Schematic of experimental setup for dual-mode emission

Complete details of this work can be found in the publication by N. A. Naderi et al "Two color multi-section quantum dot distributed feedback laser," *Optics Express* 18(26), pp. 27028-27035 (2010) [3].

The impact of varying temperature on the peak separation was studied in a follow-on paper by F. Grillot et al. in which the lasing operation was contained within the excited states of the quantum dots. In generating two single-mode emission peaks, a mode separation ranging from 1.3-THz to 3.6-THz was demonstrated over temperature, as seen below in Fig. 8 [6]. This 2nd paper demonstrated the tuning possible and some of the unique quantum dot physics.

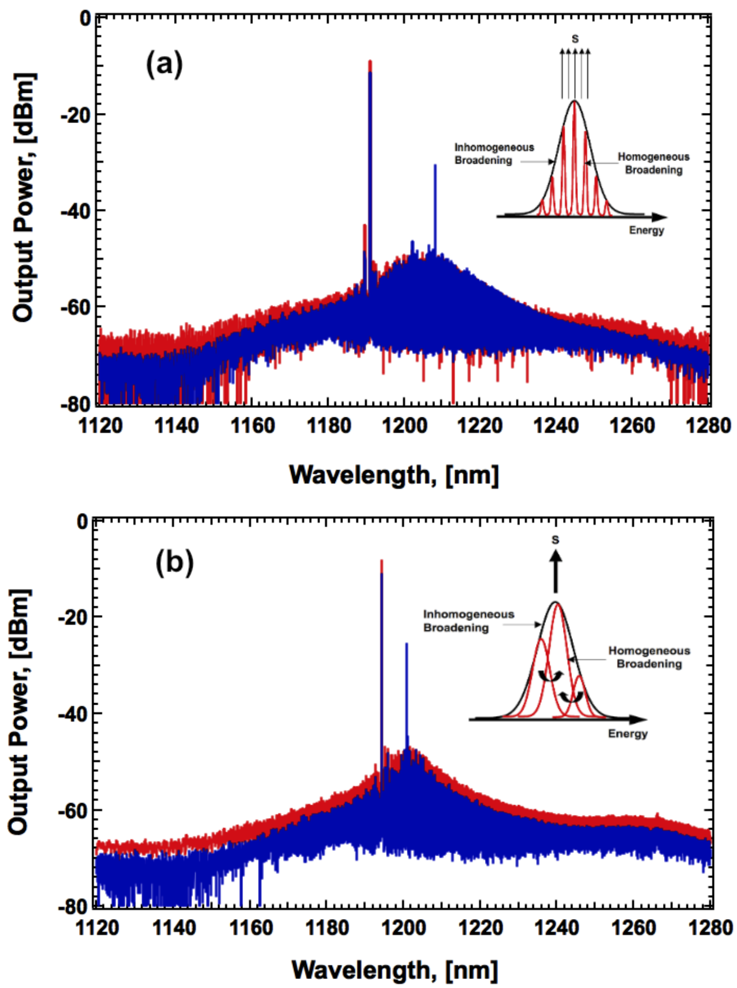


Fig. 8:. Spectra under total asymmetric pump current for the solitary laser (red) and under controlled optical feedback (blue) at (a) 5°C and (b) 40°C.

The ability to produce these two simultaneous lasing modes were attributed to the unique carrier dynamics of the quantum-dot gain medium via the excited state inhomogeneous linewidth coupled with proper external feedback control. These results are particularly important towards the development of future THz optoelectronic sources with compact size, low fabrication cost, and high performance. This work is described in detail in the paper by F. Grillot et al. "A dual-mode quantum dot laser operating in the excited state," *Applied Physics Letters* 99(23), 231110 (2011) [6].

The demonstration of dual-mode lasing from a QD-DFB laser lead to a further body of work by A. Hurtado et al, wherein tunable dual-mode lasing was experimentally demonstrated in a 1310-nm quantum dot (QD) distributed-feedback (DFB) laser under single-beam optical injection. The wavelength spacing between the two lasing modes was controlled by injecting the external optical signal into different residual Fabry-Perot modes of the QD DFB laser. A schematic of the experimental setup is shown below in Fig. 9:

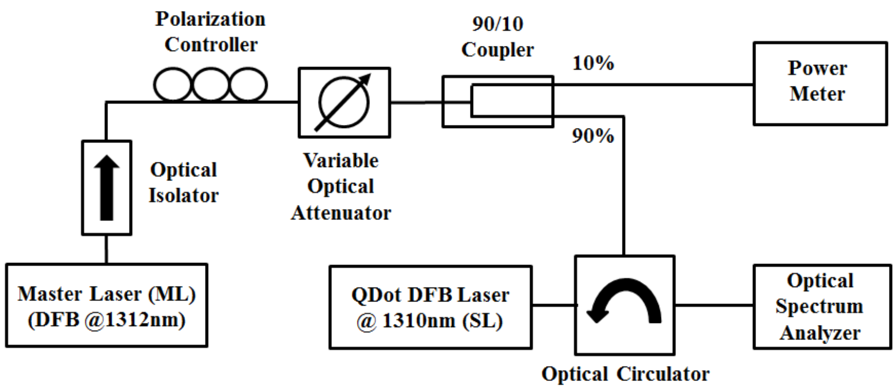


Fig. 9: Experimental setup for dual-mode lasing by optical injection into a QD-DFB laser.

Injection into a residual Bragg-mode lead to the enhancement of the same, as shown in Fig. 10 below:

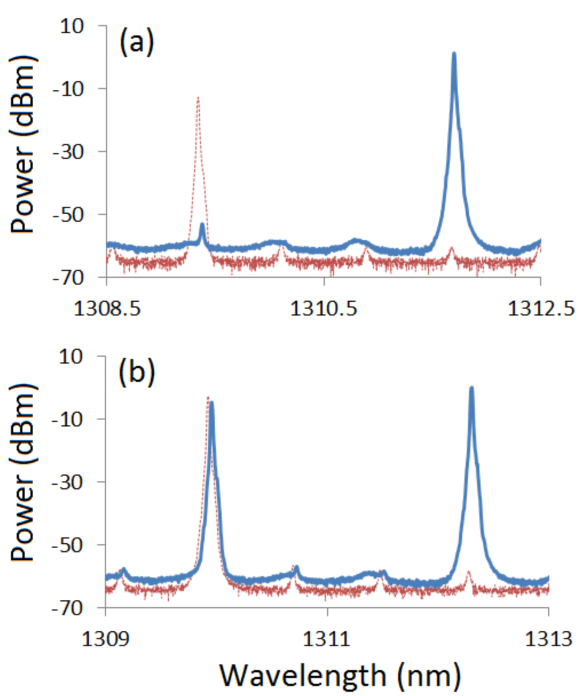


Fig. 10: Spectra of the QD DFB laser in solitary (red dashed lines) and after optical injection into the third residual FP mode in the longer wavelength side of the Bragg mode with P_{inj} = 4.8mW; Δf = -4GHz (blue solid lines). (a) I_{Bias} = 6mA and (b) I_{Bias} = 20mA.

Details of the complete study can be found in the publications by A. Hurtado et al entitled "Dual-mode lasing in a 1310-nm quantum dot distributed feedback induced by single-beam optical injection," *Applied Physics Letters* **102**, 201117 (2013) [13] and A. Hurtado, et al entitled "Generation of Tunable Millimeter-Wave and THz Signals with an Optically Injected Quantum Dot Distributed Feedback Laser," *IEEE Photonics Journal* **5**(4), 5900107 (2013).

Part III The Optical-Injected Quantum Dot DFB Laser

Lead by Profs. Michael Pochet of AFIT and Lester of UNM, we collaborated with Dr. Vassilios Kovanis of AFRL to develop a dimensionless set of equations to evaluate the operational dynamics of an optically injected nanostructure laser as a function of the injection strength and the detuning frequency to account for the large nonlinear gain component associated with nanostructure lasers through the nonlinear carrier relaxation rate and gain compression coefficient. The large nonlinear carrier relaxation rate and gain compression coefficient were shown to impact the level of stability numerically predicted in the optically injected quantum dot laser at low injected power levels. The numerical model was verified experimentally by optically injecting a quantum-dot Fabry-Perot laser with an operating wavelength of approximately 1550 nm. The quantum-dot laser's large damping rate, gain compression coefficient, and sufficiently small linewidth enhancement factor are observed to inhibit period-doubling and chaotic operation under *zero frequency-detuning* conditions. The inclusion of the nonlinear carrier relaxation rate in the simulation was shown to greatly enhance the agreement between the numerical predictions and the experimentally observed dynamics.

Even more exciting, the unique response of a quantum dot DFB laser to optical injection made for some very interesting results. Tunable microwave signal generation with frequencies ranging from below 1 GHz to values over 40 GHz were demonstrated experimentally with a 1310-nm QD DFB laser. Microwave signal generation was achieved using the period 1 relaxation oscillations induced in the QD DFB under optical injection. A *continuous* tuning in the positive detuning frequency range of the quantum dot's unique stability map was demonstrated. The conditions over which microwave signal generation due to injection-locking was achieved are determined by the shaded regions in Fig. 11(a).

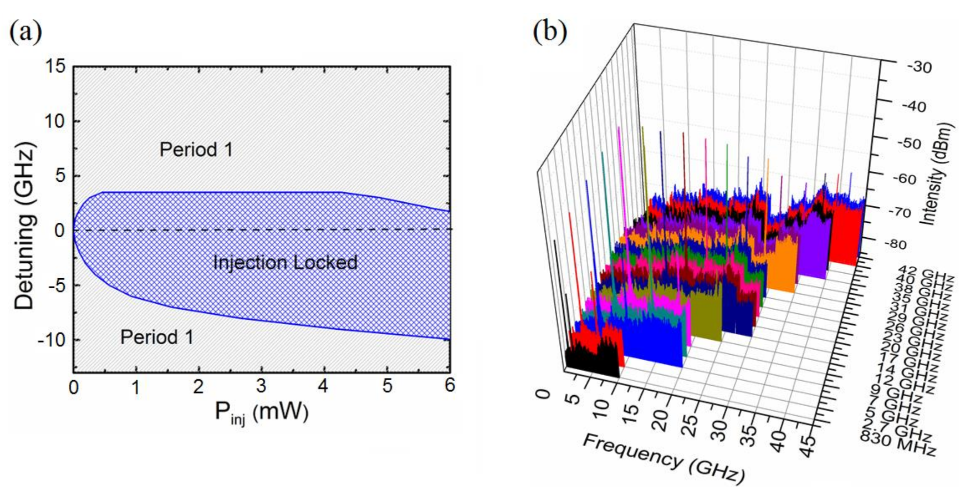


Fig. 11. (a) Stability map of the QD DFB laser at I_{Bias} = 55mA. (b) Superimposed electrical spectra generating signals with frequencies from 830 MHz to 42 GHz.

Fig. 11(b) then shows the generation of microwave signals with frequencies ranging over 5 octaves The frequency of the generated signals depends strongly on the configured initial conditions, namely the initial frequency detuning between the master laser and slave laser (Δf) and the injection strength (P_{inj}). Thus, a generated microwave signal could be tuned along this vast region of Period 1 dynamics by just controlling these two parameters. Complete details of this work have been reported in the paper by A. Hurtado et al, "Tunable microwave signal generator with an optically-injected 1310-nm QD-DFB laser," *Optics Express* **21** (9), 10772-10778 (2013).

The versatility of this technique of dual-mode lasing and signal generation was studied in further detail by A. Hurtado, whereby the generation of tunable millimeter-wave (MMW) and Terahertz (THz) signals was experimentally demonstrated with an optically-injected 1310 nm quantum dot (QD) Distributed Feedback (DFB) laser. A novel technique for MMW and THz signal generation was proposed based on the dual-mode laser operation and the four wave mixing induced in the QD DFB under single-beam optical injection into one of its residual Fabry-Perot modes. Crucially, both coarse and fine tunability of the MMW and THz signals from 117 GHz to 954 GHz were demonstrated by injecting the external light into different residual modes of the QD laser and by controlling the injection strength and the initial frequency detuning. Key results can be seen below in Fig. 12a.)-f.).

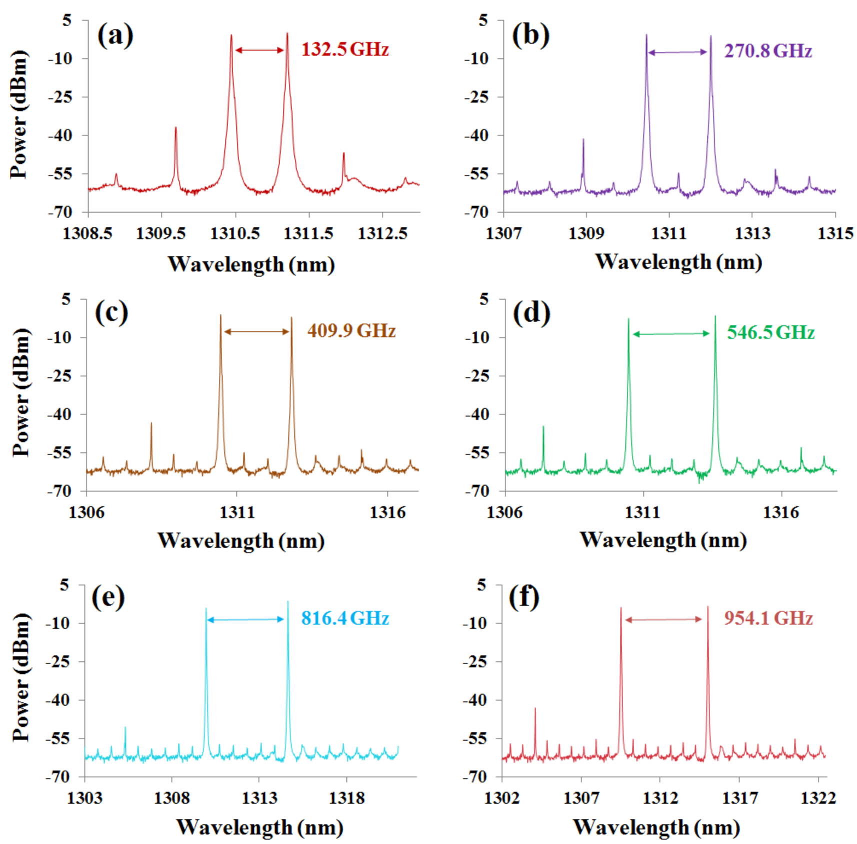


Fig. 12. Optical spectra measured at the output of the QD DFB laser when an optical signal is injected into the (a) first, (b) second, (c) third, (d) fourth, (e) sixth and (f) seventh longer wavelength FP modes. MMW and THz signals at ≈ 132.5, 270.8, 410, 546.5, 816.4 and 954.1 GHz are generated as indicated. P_{inj} = 2.4mW and Δf = 0 GHz in all cases. (a-d) I_{Bias} = 30mA; T_{SL} = 25C; (e) I_{Bias} = 20mA; T_{SL} = 25C and (f) I_{Bias} = 30mA; T_{SL} = 15C.

Complete details of this work have been reported in the recent publication by A. Hurtado et al, entitled “Generation of Tunable Millimeter-Wave and THz Signals with an Optically Injected Quantum Dot Distributed Feedback Laser,” *IEEE Photonics Journal* **5**(4), 5900107 (2013).

Interactions/Transitions:

On the theory/numerical simulation side, our primary interactions were with Dr. Vassilios Kovanis of AFRL/RYDP (Wright Patterson AFB, Dayton, OH). We participated in several conference and meetings and in the Photonics community including Photonics West 2011, 2012 and 2013 in San Francisco, the 2011 IEEE Photonics Conference in Arlington, VA and the 2012 International Semiconductor Laser Conference in San Diego, CA. Furthermore, this project supported the work of four graduate PhD at various stages of their studies as described below. From October 2011 through May 31, 2013, Dr. Antonio Hurtado, a Marie Curie Fellow, was in residence at UNM and collaborated with us on numerous experiments related to the optical feedback and dual-mode lasing efforts. Prof. Frederic Grillot of Telecomm-Paristech in France was a vital collaborator in the feedback experiments of the quantum dot mode-locked laser and the early development of the dual-mode quantum dot laser.

Personnel Supported

PhD student Ravi Raghunathan, who graduated in Summer 2013, worked on the delayed differential equation (DDE) modeling of the quantum dot mode-locked laser for this grant project. Dr. Raghunathan is now a postdoctoral fellow at Virginia Tech. PhD student Jesse Mee, who graduated in Summer 2013, worked on the high-speed testing of the quantum dot mode-locked laser over temperature. Dr. Mee is a research scientist for AFRL/RVSE at Kirtland Air Force Base in Albuquerque, NM. PhD student Chang-Yi Lin, who graduated in Spring 2011, characterized the phase noise and jitter of the quantum dot mode-locked laser and developed their associated operating equation. Dr. Lin now works for Intel in Hillsboro, Oregon. Finally, PhD student Nader Naderi, who graduated in Summer 2011, first developed and published the dual-mode quantum dot laser. Dr. Naderi spend 2 years as an NRC Fellow at AFRL/Kirtland.

Journal Publications from Year 1 (Including citation count from Google Scholar)
These publications acknowledge the AFOSR grant number

1. C.-Y. Lin, F. Grillot, Y. Li, R. Raghunathan, and L. F. Lester, "Characterization of timing jitter in a 5 GHz quantum dot passively mode-locked laser," *Optics Express* 18(21), pp. 21932-21937 (2010). (11 citations)
2. C.-Y. Lin, F. Grillot, N. A. Naderi, Y. Li, and L. Lester, “ rf linewidth reduction in a quantum dot passively mode-locked laser subject to external optical feedback”, *Applied Physics Letters* vol. 96, pp. 51118 - 051118-3 (2010). (18 citations)
3. N. A. Naderi, F. Grillot, K. Yang, J. B. Wright, A. Gin, and L. F. Lester, “Two color multi-section quantum dot distributed feedback laser,” *Optics Express* 18(26), pp. 27028-27035 (2010). (13 citations)

Journals and Conference Papers from Year 2

4. C.-Y. Lin, F. Grillot, N.A. Naderi, Y. Li, R. Raghunathan, and L.F. Lester, "Microwave Characterization and Stabilization of Timing Jitter in Quantum-Dot Passively Mode-Locked Laser via External Optical Feedback," *IEEE J. Special Topics Quantum Electron*., **17**(5), 1311-1317 (2011). (8 citations)
5. M. C. Pochet, N. A. Naderi, V. Kovanis, and L. F. Lester, "Modeling the Dynamic Response of an Optically-Injected Nanostructure Diode Laser," *IEEE J. Quantum Electron*., **47**(6), 827-833 (2011). (8 citations)
6. F. Grillot, N. A. Naderi, J. B. Wright, R. Raghunathan, M. T. Crowley, L. F. Lester, "A dual-mode quantum dot laser operating in the excited state," *Applied Physics Letters* **99**(23), 231110 (2011). (9 citations)
7. R. Raghunathan, M. T. Crowley, F. Grillot, S. D. Mukherjee, N. G. Usechak, V. Kovanis, and L. F. Lester, "Delay Differential Equation-Based Modeling of Passively Mode-Locked Quantum Dot Lasers using Measured Gain and Loss Spectra" *SPIE Proceedings* of Photonics West 2012.
8. R. Raghunathan, M. T. Crowley, F. Grillot, V. Kovanis and L. F. Lester, "Direct Characterization of Carrier Relaxation in a Passively Mode-Locked Quantum Dot Laser", IEEE Photonics Conference, Virginia, (2011).

Journals and Conference Papers from Year 3

9. A. Hurtado, I. D. Henning, M. J. Adams, and L. F. Lester, "Generation of Tunable Millimeter-Wave and THz Signals with an Optically Injected Quantum Dot Distributed Feedback Laser," *IEEE Photonics Journal* **5**(4), 5900107 (2013).
10. R. Raghunathan, M. T. Crowley, F. Grillot, Y. Li, J. K. Mee, V. Kovanis, and L. F. Lester, "Pulse Characterization of Passively Mode-Locked Quantum-Dot Lasers Using a Delay Differential Equation Model Seeded with Measured Parameters," *IEEE J. Sel. Top. Quantum Electronics* **19**(4), 1100311 (2013).
11. A. Hurtado, M. Nami, I. D. Henning, M. J. Adams, and L. F. Lester, "Two-Wavelength Switching with a 1310-nm Quantum Dot Distributed Feedback Laser," *IEEE J. Sel. Top. Quantum Electronics* **19**(4), 1900708 (2013).
12. J. K. Mee, M. T. Crowley, D. Murrell, R. Raghunathan, and L. F. Lester, "Temperature Performance of Monolithic Passively Mode-Locked Quantum Dot Lasers: Experiments and Analytical Modeling," *IEEE J. Sel. Top. Quantum Electronics*, **19**(4) 1101110 (2013).
13. A. Hurtado, I. D. Henning, M. J. Adams, and L. F. Lester, "Dual-mode lasing in a 1310-nm quantum dot distributed feedback induced by single-beam optical injection," *Applied Physics Letters* **102**, 201117 (2013). (2 citations)
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16. J. K. Mee, M. T. Crowley, N. Patel, D. Murrell, R. Raghunathan, A. Aboketaf, A. Elshaari, S. F. Preble, P. Ampadu, and L. F. Lester, "A passively mode-locked quantum-dot laser

operating over a broad temperature range," *Applied Physics Letters* **101**(7), 071112 (2012). (4 citations)

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18. R. Raghunathan, M. T. Crowley, F. Grillot, J. K. Mee, V. Kovanis, and L. F. Lester, "Modeling and characterization of pulse shape and pulse train dynamics in two-section passively mode-locked quantum dot lasers," *SPIE Proceedings* of Photonics West 2013.
19. J. K. Mee, M. T. Crowley, N. Patel, D. Murrell, R. Raghunathan, A. Aboketaf, A. Elshaari, S. F. Preble, P. Ampadu, and L. F. Lester, "110°C Operation of Monolithic Quantum Dot passively Mode-Locked Lasers," *International Semiconductor Laser Conference* 2013.

New Discoveries, Inventions or Patent Disclosures

None.

Honors/Awards

Professor Luke F. Lester received the 2012 Harold E. Edgerton Award from SPIE, The International Society for Optics and Photonics "In recognition of his pioneering contributions to the development, characterization and integration of quantum dot mode-locked lasers as high-speed optical sources."

Professor Lester became an IEEE Fellow in 2013 "for contributions to quantum dot lasers." He also became an SPIE Fellow in 2013.